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Solar cells and the applications engineer

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Knowledge of cell characteristics and performance having recently become much more precise, the engineer can now treat system designs with greater skill and efficiency

Reprint

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[5p]

In the past decade, solar cells have advanced from the primitive, with about 4–5% efficiency, to the refined, incorporating anti-reflecting and heat-dissipative coatings and having efficiency as high as 14–14.5%. Solar cells have, of course, seen extensive use on spacecraft, and will continue to do so for at least five years. Knowledge of solar cells has recently become much more precise. This will affect applications. Our discussion consequently reviews and summarizes data useful to the applications engineer.

Cell power output is light- and temperature-dependent, and affected by high-energy radiation particles. The top left graph on page 55 shows typical open-circuit voltages and short-circuit current properties of the new N/P 1-ohm-cm cell as a function of light intensity. Current shows an almost linear function of illumination from zero to beyond 1-sun intensity (140 mw/cm²), while voltage begins to saturate at very low illumination and increases only slightly with increasing intensity.

The table on page 56 gives typical 100-mw/cm² tungsten-light characteristics for 1-ohm-cm base-resistivity silicon cells. Temperature has a serious effect on the cells. Short-circuit current increases slightly with temperature to over 100 C, while open-circuit voltage decreases at about 0.00252 V/C. Because of voltage degradation and change in current, cell efficiency at 125 C drops to about half that of room temperature value.

Maximum power is obviously affected by temperature and illumination. I-V curves representing performance of typical 1-ohm-cm N/P cells at various temperatures and illuminations are shown in the second and third illustrations on page 55.

Bare-solar-cell power output follows the cosine law for incident radiation. Space applications require the use of protective cover glasses, which can complicate this rule because of multiple interfaces and reflections. Sample modules of the spacecraft solar-cell array should be evaluated under good sunlight conditions to determine more accurately the power output as a function of the angle of sunlight incidence.

Light sources, moreover, can greatly influence solar-cell efficiency. Solar cells are spectrally selective devices and can give misleading information about their performance in outer space when measured under artificial light. The normal sensitive range of the so-called "blue-shifted" silicon solar cell is between 0.35 and 1.1 micron, with a bell-shaped response curve peaking near 0.8 micron. (The human eye responds to light between 0.4 and about 0.7 micron, with a peak response near 0.56 micron). If one used a normal-incidence pyrheliometer to calibrate light sources, considerable error could be observed in trying to determine the efficiency of a given silicon solar cell. Using a monochromatic source of 0.8-micron light set to 100 mw/cm² by the pyrheliometer, the solar cell might display a conversion efficiency of 50% or more. Next, if a tungsten-light source at 2800 K were displaced from the pyrheliometer, so that again a 100 mw/cm² was incident, the solar cell would read an efficiency of perhaps 13%. Outside on a clear, bright summer day, the pyrheliometer could indicate 100 mw/cm², and the same solar cell might now perform with an efficiency of about 11.7%. In earth orbit (air-mass zero) this cell would show an efficiency of about 10%.

These examples illustrate the large errors that can result by improper standards and calibration techniques, which were rather widely predominant only a short while ago. Measurements made on the ground in natural sunlight and then at altitudes near 77,000 ft from balloons showed between 13 and 17% degradation of solar-cell efficiency.[1] Even though 40% more solar power is available at air-mass zero than under ideal conditions on the ground, and the solar cell delivers more power to its load at air-mass zero, it performs less efficiently at a given temperature.

This may be illustrated by a graph on page 56. At air-mass one, a pyrheliometer sees the solar energy illustrated under the solid line (moon's data), but the solar cell responds only to the energy shown within the lower shaded area. At air-mass zero, the pyrheliometer responds to the solar

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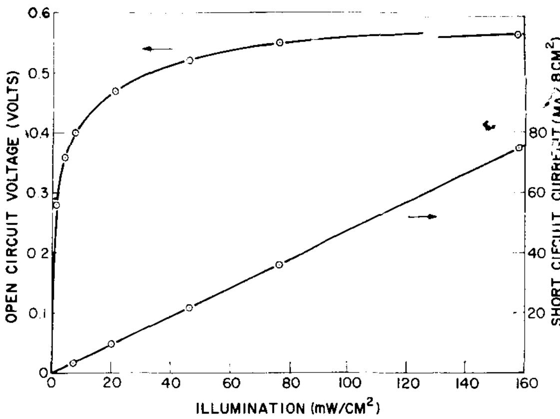
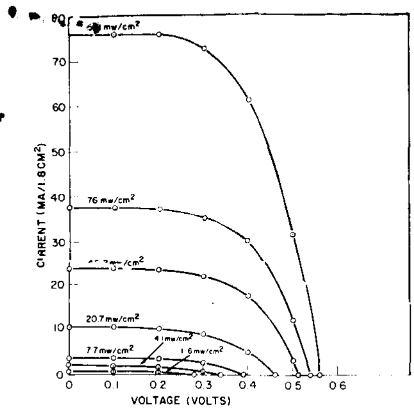
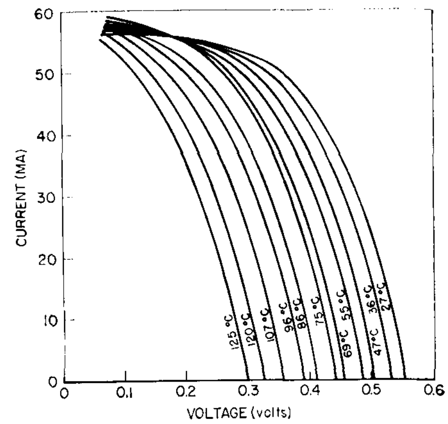


Open circuit voltage and short circuit current vs. illumination of new 1-ohm-cm N/P cell.



Typical 1-ohm-cm N/P cell characteristics vs. illumination at 25 C.



Current-voltage vs. temperature for the 1-ohm-cm N/P cell.

energy represented under the dashed line (Johnson's data), but again the solar cell can utilize the solar energy shown only within the total shaded areas. Although it utilizes more energy at air-mass zero, this is a smaller percentage of the total than under air-mass-one conditions, thus yielding a lower conversion efficiency.

It becomes obvious that a pyrheliometer cannot be used conveniently to adjust artificial light sources for calibrating solar cells. Representative cells from a given process may be calibrated in air-mass-one sunlight, and then these cells may be used to adjust 2800 K tungsten sources to attain the same general I-V characteristics observed outside. The artificial source may now be used to *compare* other cells from the same process with the standards used to calibrate the light. This artificial light source cannot be used, however, to determine the natural-light performance of solar cells made by different processes, with different junction depths or different base resistivities, similar cells using different anti-reflection coatings, or cells made from different semiconductor materials. Change any of the aforementioned variables, and typical cells of that variety will have to be evaluated in natural light so that the artificial source can be properly calibrated.

Today both P/N and N/P solar cells are available. They are large-area diodes, having a region in the silicon-doped p-type and another region doped n-type. The early work of Pearson, Chapin, and Fuller at BTL in 1953 and 1954 resulted in the diffusion of boron (a p-type dopent) into a wafer of lightly phosphorus-doped silicon (n-type).[2] In those days, the boron-diffusion process was more advanced and resulted in superior performance of the P/N silicon solar cell. The industry utilized the BTL "know-how" to put this solar cell into production.

Then, in 1958 a Russian spacecraft was reportedly equipped with N/P solar cells. These cells were not commercially available in the U.S. and had not been thoroughly investigated. Mandelkorn at the U.S. Army Signal R&D Lab at Fort Monmouth, N.J., became interested in comparing the properties of both types of cells to see if there was any substantial difference between them.[3] By late 1959 and early 1960, high-quality phosphorus-diffused N/P cells were available for study by Mandelkorn's group. Basically, the N/P cells as made by the Signal Corps showed substantially lower leakage currents and somewhat better diode characteristics than generally available P/N cells. In May 1960, cells were subjected to electron radiation damage experiments and unexpectedly revealed at least 10 times superior resistance to 1-Mev-electron damage than comparably efficient P/N cells.

At least two things contribute to this observed result. Since the operation of the silicon solar cell depends to a large extent on the collection of photon-generated carriers deep within the material, these carriers must be able to traverse relatively long distances (up to 150 microns) in the bulk silicon. To do this, the generated carriers must have a long lifetime. It is well known that the lifetime of minority carriers (electrons) in p-type materials is about three times that of minority carriers (holes) in n-type material. Secondly, it takes more energy to create a defect in p-type than in n-type material. The reason for this is not clearly understood. The defects act as traps and seriously reduce the lifetime, and consequently the diffusion length, of the minority carriers.

The combination of these two factors, and probably others not now understood, contribute to make the N/P solar cell more radiation resistant to both protons and electrons, although not to the same degree, as will be shown later.

At present, the N/P fabrication process is still being worked out to gain optimum yields and maximum solar-cell èfficiency. Mandelkorn was able to fabricate N/P cells comparable in every respect to the best P/N cells. Because of the control and properties of the N/P process, higher yields of high-quality cells with more-uniform characteristics will result after large-scale production begins.

Radiation damage to solar cells can be reduced; and indeed, the study of radiation damage to solar cells has been pursued in great earnest since the actual measurement of high-energy particles in the natural and artificial radiation belts. Cells have been irradiated with electrons, protons, and neutrons in energies from a few Kev to more than 700 Mev. The particles of most interest to the solar-cell user are electrons with energies from about 0.5 to 10 Mev and protons from 0.5 to 40 Mev. These are the principal energy ranges found in the natural and artificial earth radiation belts thought to account for the main degradation of the cells due to high-energy particles.

The lowest particle energy which causes damage to a solar cell is called the threshhold energy. About 170-Kev electrons will begin to damage P/N cells, while about 250-Kev electrons begin to damage N/P cells. The particle dosage which causes a 25% power degradation of a solar cell is defined as the critical flux. About 10^{18} electrons/cm^2 is the critical flux for each type of cell at its respective threshhold energy. As the bombarding electron energy is increased to 1.0 Mev, the critical flux decreases. However, at all given energies, a greater total dosage is required to reduce the N/P cells' maximum power by the same amount as the P/N cell. At 1 Mev it is necessary to subject the N/P cell to over 10 times the dosage of a P/N cell to cause similar power degradation. The graph here below at the top right displays this advantage of the N/P cell.[4] Recently it has been observed that electrons over 2 Mev cause appreciably more damage than anticipated.

Experiments with protons at 8 and 19 Mev show a similar trend,[5] but the N/P cell displayed only a factor of about 3 enhancement over the P/N. Critical dosages of protons are about $3.5 \pm 2 \times 10^{10}$ for P/N cells and $8.4 \pm 1 \times 10^{10}$ protons/cm^2 for N/P cells at an energy of 8 Mev.

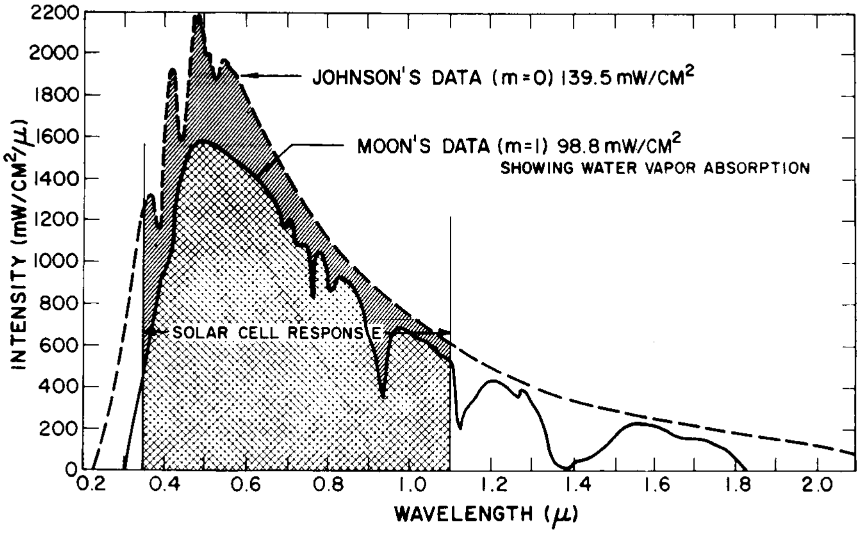
Since the electron has small mass compared with a proton, its energy is associated with a relatively larger velocity than the proton's. For a given energy, consequently, an electron is much more difficult to stop than a proton.

An obvious means of reducing satellite power degradation by these high-energy particles is to utilize the N/P solar cell. In addition, cover glass must be used to stop or appreciably reduce the energy of all particles possible. This now becomes a compromise between weight and life of the satellite. To stop 1-Mev protons, 2.65 gm/cm^3 quartz cover glasses 0.5 mil thick would be required.[6] To stop 1-Mev electrons, around 65 mils of quartz is needed. To stop the higher-energy electrons (4 Mev) observed in the artificial radiation belt, 300 mils of quartz is necessary. Protons with energies of 40 Mev have been measured in the natural belts. To stop these particles, 225 mils of quartz is required. A 2.65-gm/cm^3 quartz cover 1 sq ft by 225 mils thick would weigh 3.1 lb. Since it is impractical to stop all radiation damage to solar cells, power systems are designed to allow for a 25-50% degradation in power if very long life is required.

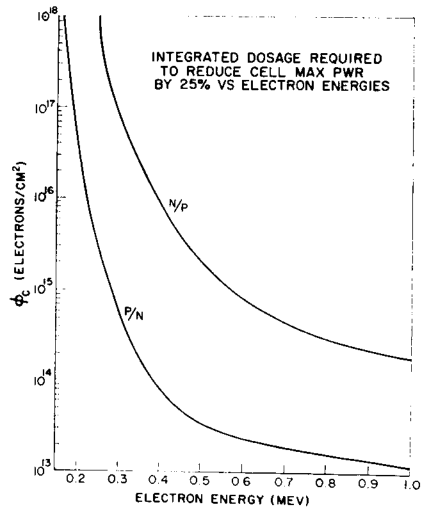
Another factor has recently become apparent that will permit the further enhancement of radiation resistance of solar cells. The impurity level of the silicon used to make semiconductor devices is frequently expressed in terms of ohm centimeters. Cells made by the Western Electric Co. and used on Telstar were made with 1-ohm-cm p-type silicon. Work at NRL irradiating base-resistivity cells ranging from 1-80 ohm cm with 4.8 Mev protons showed a definite improvement in resistance to degradation of minority-carrier diffusion length and hence power output with increasing base resistivity.[7]

A recent experiment, cooperatively planned between NRL and the author,[8] using 1-Mev electrons, subjected 1-, 10-, and 25-ohm-cm solar cells to various dosages from 10^{11}-10^{16} electrons/cm^2. The graph at bottom shows the results. Again, a distinct improvement in radiation resistance was found in going to higher-base-resistivity silicon. The optimum point between performance and radiation-damage resistance has not as yet been established, but at this time appears to be somewhere between 1 and 10 ohm cm.

The question frequently arises, what should be a good power-to-weight ratio for a spacecraft solar power system?



Solar spectrum at air mass one and air mass zero, illustrating how solar-cell performance can be substandard.

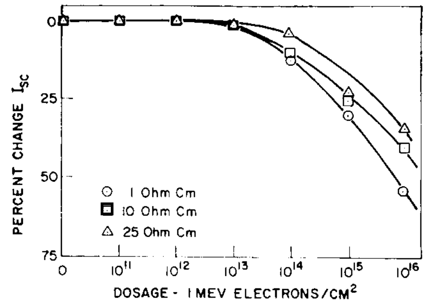


Integrated dosage to reduce cell max. power by 25% vs. electron energy.

TYPICAL CHARACTERISTICS OF 1-OHM-CM N/P SILICON SOLAR CELLS

Characteristics	Avg. Value Observed	Range Low	Range High
25 C V_{oc}	0.572 V	0.560 V	0.590 V
25 C I_{sc}	48.0 ma	41.8 ma	52.5 ma
Change in V_{oc}/C	0.00252 V/C	0.00246V/C	0.00253 V/C
Change in P_{mp}/C	0.098 mw/C	0.084 mw/C	0.113 mw/C
% Change in Eff/C	0.56%/C	0.53%/C	0.60%/C

Note: Nominal 1- by 2-sq cm cells, characteristics measured at 100 mw/cm^2 with 2800-K tungsten light through 3-cm water bath. Data from experiments performed at Goddard SFC in February and March 1963.[10]



Comparison of base resistivity with per cent change in short circuit due to 1 mev electrons.

Craft	Stability	Cell Mounting	Weight, lb Array	Weight, lb Storage	Weight, lb Pwr. Syst.	Watts at ⊥ incidence	Watts/lb Array	Watts/lb System	Array area, sq ft	Over-all w/sq ft
OAO	Non-oriented	Paddles	222	177	399	772[a]	3.65	1.94	187	4.14
OSO (S-16)	Oriented	Panel	5.2	30.7	35.9	31[b]	6.0	0.86	4	7.7
EGO	Oriented	Panels	127	74	201	560[c]	4.4	2.8	78	7.2
Relay	Non-oriented	Body	25.8	28	53.8	35	1.4	0.65	17.6	2.0
Nimbus B	Oriented	Panels	64	113	177	410	6.4	2.3	43	9.5
Tiros[d] (Alpha = 45°)	Non-oriented	Body	24.5[e]	40	64.5	51	2.1	0.79	17.7	2.9
Tiros[d] (Alpha = 90°)	Non-oriented	Body	24.5[e]	40	64.5	25	1.1	0.39	17.7	1.4
UK-1	Non-oriented	Paddles	8.8	14	22.8	11.7	1.3	0.52	11.0	1.1

[a] Average power output from cold panel to hot panel is 772 w.
[b] At 70 C.
[c] At 60 C.
[d] Alpha = 45 or 90 deg is inclination of sun to spin axis.
[e] Does not include aluminum housing over instruments upon which cells are mounted.

Unfortunately, this is a difficult thing to define, depending as it does on several factors.

First, the altitude and inclination of the orbit must be considered. A meteorological spacecraft like Nimbus will have periods of 68 min in sunlight and 35 min in darkness. Other spacecraft in polar orbit, such as the S-27 Canadian Alouette, enjoy cycles always in the sunlight. Still others with long elliptical orbits, such as Explorer XII, see 26 hr of sunlight and about 1/2 hr of darkness. IMP will have nearly seven days of sunlight and a maximum of 1/2 hr of eclipse. The solar-panel and storage systems of these craft are all considerably different from one another.

Then, the "on time" operation of the satellite can have a large influence on the power-system design. Some craft take data, store it, and then transmit at various intervals on command—for example, Telstar, Relay, and Nimbus. Others are more or less continuously in operation, like OAO. There is also a considerable difference in the solar-cell panel design if it is oriented or spinning, panel-mounted, paddle-mounted, or body-mounted. Generally, body-mounted systems can dissipate their heat throughout the spacecraft and thus run cooler than paddle- or panel-mounted systems in the sun.

The table here gives some comparative figures on various spacecraft. Taken as the point of comparison is the total power developed by the solar array at normal incidence to the sun, unless otherwise noted. Converter and battery efficiencies are not taken into account. The array weight is defined as the total weight of cells, cover glasses, adhesives and solders, substrates, and any support structures associated with the paddles or panels. On body-mounted spacecraft, only those weights associated with the panel mounting solar cells are considered. Battery storage weights include the weight of the cells, cases, mounting brackets, and all cables and accessories associated with the storage system, but not the converter or regulator system. The power output is based on "first day in orbit" conditions and does not show radiation-damage degradation.

Solar cells will be used as the primary power source on spacecraft with missions of three months' or more duration for at least the next five years. The cells are still very expensive and offer array (less than 7) and system (less than 3) w-to-lb ratios for oriented and nonoriented systems, respectively. Radiation damage soon reduces these factors appreciably.

Looking to the future, research into thin-film solar converters is well underway. Some experimental arrays using cadmium-sulphide have demonstrated watt-to-pound ratios as high as 20, even though the converter is around 2% efficient. Small-area cadmium-telluride films have shown sunlight conversion efficiencies of 6%.[9] Film converters should be inexpensive to make in relatively large areas, for instance, a square foot. Since the devices will be less dependent on collection of carriers from deep within the cell, they should be more radiation-resistant.

In addition, gallium arsenide and gallium phosphide are being investigated for their special properties as solar cells. Single-crystal gallium arsenide cells with sunlight efficiencies as high as 11% have been measured recently. Temperature and radiation-resistant properties appear in general to be superior to silicon except for low-energy protons (below 1 Mev). These can be easily shielded with thin cover glasses. However, cost of gallium arsenide cells is very high.

The early state of the art of the other materials has prevented the fabrication of good-quality solar cells.

As solar-cell power systems approach the kilowatt range, improved erection and orientation techniques will have to be developed. Launch conditions require the solar panels to be folded or rolled to fit under the missile's shroud. Thin-film structures appear particularly attractive for this reason.

Recent development of high-quality V-ridge concentrators may permit a substantial increase in the power available to the spacecraft, yet only increase the number of cells by about 20%. Concentrators could conceivably be stacked or folded in such a way that double the array area, that is now feasible, will be possible and still fit under the booster shroud.

Acknowledgment

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